Towards a Perturbative Theory of Nuclear Forces*

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The last decade has seen significant progress toward the formulation of an effective field theory (EFT) description of multi-nucleon systems. The importance of uncovering such an EFT cannot be overstated as it is this theory alone that will allow for rigorous calculations of both elastic and inelastic processes in multi-nucleon systems in a framework consistent with the Standard Model of strong and electroweak interactions. An inherent advantage of an EFT framework is that the uncertainty associated with the computation of any given observable can be estimated and controlled with the power-counting scheme that defines the theory (along with the regulator). The fundamental difficulty in formulating power-counting schemes for multi-nucleon systems is that the interaction of two or more nucleons near threshold is intrinsically nonperturbative. This manifests itself through the presence of scattering lengths that are much larger than one would naively expect from QCD, $\sim \Lambda_{QCD}^{-1}$. For very low-momentum processes, such as $np \to d\gamma$ in the nucleosynthesis region, a consistent and converging EFT, has been developed to describe strong and electroweak processes in multi-nucleon systems. However, attempts to develop a fully consistent theory to describe processes involving momenta larger than the mass of the pion have so far been unsuccessful.

Weinberg's (W) original proposal for an EFT describing multi-nucleon systems was to determine the nucleon-nucleon (NN) potentials using the organizational principles of the well-established EFTs describing the meson-sector and single-nucleon sector (chiral perturbation theory), and then to insert these potentials into the Schrödinger equation to solve for NN wavefunctions. Observables are computed as matrix elements of operators (that have their own chiral expansion in this EFT) between these wavefunctions. Unfortunately, there are formal inconsistencies in W power counting, in particular, divergences that arise at leading order (LO) in the chiral expansion cannot be absorbed by the LO operators. Problems persist at all orders in the chiral expansion, and the correspondence between divergences and counterterms appears to be lost. This formal issue was partially solved by Kaplan, Savage and Wise (KSW) who introduced a power counting in which pions are treated perturbatively. Further studies however showed that the KSW expansion converges slowly in the ${}^1S_0$ channel and does not converge at all in the ${}^3S_1 - {}^3D_1$ coupled channels.

We proposed in this paper that a consistent expansion can be obtained by expanding around the chiral limit. In the triplet channel this involves a resummation to all orders of the tensor force, as is done in W counting, but the singlet channel remains perturbative. In this sense the proposed expansion is a mix between the KSW and the W power counting. A bizarre feature that emerges from the nonperturbative nature of the ${}^3S_1 - {}^3D_1$ coupled channels is the scaling of operators with fractional powers of the chiral symmetry-breaking scale, e.g. $D_2 \sim \Lambda_\chi^{-3/2}$.

[1] Silas R. Beane, Paulo F. Bedaque, Martin J. Savage, Ubirajara van Kolck, *Nucl.Phys.A700:377-402,2002*